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NUMERICAL PARAMETRIC STUDY OF CRACK PARAMETERS NEAR CRACK TIP

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ABSTRACT

It is necessary to measure accurately crack tip parameters to analyze crack and rate of crack propagation in fracture mechanics. Numerous efforts have been made towards the determination of stress intensity factor (SIF) and other crack parameters using experimental and analytical methods after the pioneer work of Irwin. Stress intensity factor is the parameter which determines, whether the crack in the material is critical or not. The stress intensity factor depends on the specimen geometry, crack geometry and the magnitude of load applied. This paper discusses the application of ANSYS in calculating crack parameters and discusses the effect of various crack parameters, on the stress intensity factor and the crack mouth opening displacement (CMOD), by simulating the crack. The SIF and CMOD has been calculated at several crack mouth opening angles, different crack lengths and different loads for mode-Ifracture under bending, using a side edge notch bending specimen. It has been found that, the CMOD and SIF decreases with crack angle, CMOD increases with crack length, whereas a mixed effect can be noticed in SIF with an increase in crack length.

***KEYWORDS** Stress Intensity Factor (SIF), Crack Mouth Opening Displacement (CMOD), ANSYS, Side Edge & Notched Bending (SENB)*

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INTRODUCTION

Fracture mechanics is the field of mechanics, which deals with the initiation & propagation of crack and failure of the system. Fracture mechanics was first developed by Griffith during World War I [1]. Griffith's theory was largely ignored by the engineering community until the early 1950s. In late 1950, Irvin [2] and his team considered the worth of Griffith's work and proceeded further with their study of fracture in ductile material. This was the time when they first coined the term Stress Intensity Factor (SIF) in fracture mechanics. Since then, the determination of the Stress Intensity Factors (SIFs) has become an integral task in fracture mechanics. SIF has become the prime parameter to decide whether a crack is crucial on not.

In order to prevent fracture, it is important to determine accurate value of SIF, which resulted in the development of large numbers of analytical, numerical and experimental techniques to determine SIFs. Several methods such as photo elasticity [3], caustics [4], Digital Image Correlation (DIC) [5], holography[6] and strain gauge method[7] have been used rigorously to experimentally determine the values of SIF and CMOD. All these experimental technique needs the real material to be loaded under specific conditions and an accurate and precise data collection. The degree of accuracy of SIF values determined experimentally can get affected to a great extent owing to the physical conditions, vibrations of the machine, operators accuracy etc. And, hence numerical

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techniques are now being promoted over experimental technique to extract the crack data

Numerous numerical analyses have been carried out in the past to calculate the near crack tip data. Lin and Abel [8] employed finite element method (FEM) to calculate mode-I SIF. Hwang and Ingraffea [9] used FEM to study multiple crack in a system. Reddy and Rao[10], used fractal finite element method (FFEM) to analyze cracks in a homogeneous, isotropic, and two-dimensional linear-elastic body subject to mixed-mode (modes I and II) loading conditions. Leung et al. [11] used finite element discretized method, to calculate the stress intensity factor for mode-I crack.

The stress intensity factor depends on several factors out of which, the crack geometry is the most influential. Crack mouth opening angle, tip radius, depth of notch and the crack length affects the stress intensity factor the most. Leguillon and Yosibash [12] investigated the effect of notch tip radius on the start of the crack. Later M. Saravani et al. [13] used photo elasticity method, to investigate the effect of crack's parameter, namely opening angle and crack length in mode I loading. Stanislav SEITL et al. [14], simulated a three point bending test for a chevron notched specimen, using ANSYS and compared the results with experimental results conducted by NASA. The result of the simulation is almost same as that of the experimental result, which shows that, ANSYS can be used for the computation of SIF and other crack parameters.

Developed cracks in a material can advance in different shapes. The V- notched crack is the most general case for initiation of crack in engineering structures. V-notch in any structure increases noticeably the risk of fracture. For the safe operation of the structure it is necessary to have a detailed understanding of stresses around the crack tip. Stress intensity factor fulfill all the needs required to determine the criticality of a crack.

The present study deals with the numerical modeling of a V-notch crack having different notch angles and crack length and also investigates the effect of the crack length, opening angle, magnitude of load applied on the stress intensity factor, the Crack Mouth Opening Displacement and stress at crack tip.

NUMERICAL COMPUTATION

ANSYS has been used for quite some time to simulate the real time problems. It has proved its worth as the results obtained from simulation remains close to the experimental or analytical results. It can also be used to calculate the CMOD and SIF for a crack. In order to verify the usefulness of ANSYS to calculate the crack parameters i.e. CMOD and SIF, the simulated results have been compared with the experimental results of Chandra Shekhar and Hira Lal Yadav[6] available from the literature, for the specimen shown in figure 1. Speckle metrology was used in the experiments to obtain the crack parameters. The comparison of the two results has been shown in table 1.

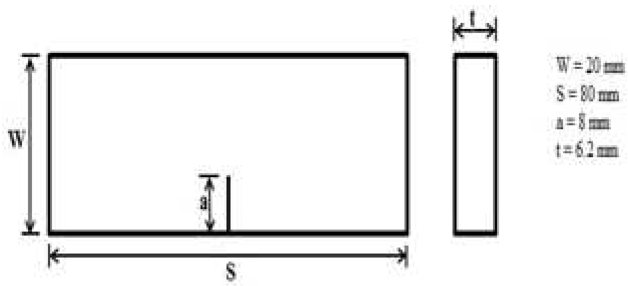


Figure 1: Typical Geometry of Specimen Used for Validation Taken from Literature [6]

Table 1: Comparison of the Simulated Result with the Experimental Result

Sl. No.	Load (N)	CMOD		SIF		Percentage deviation of CMOD (%)	Percentage deviation of SIF (%)
		ANSYS (µm)	Exper. (µm)	ANSYS ($MPa.m^{1/2}$)	Exper. ($MPa.m^{1/2}$)		
1	50	1.92	1.90	7.38	7.28	1.05	1.374
2	70	2.70	2.66	10.34	10.30	1.50	0.4
3	90	3.47	3.42	13.29	13.18	1.46	0.89
4	110	4.23	4.57	16.25	16.22	7.44	0.21

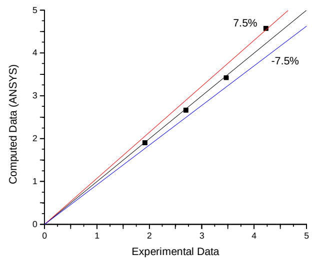


Figure 2: Comparison of Computed Data and Experimental Data

The comparison of the two data has also been done using plot shown in figure 2. According to the plot the data values lies within the error range of ± 7.5%. The above comparison of the results shows that ANSYS can be used to calculate the parameters of crack. And hence, can be applied to different geometries in order to compute SIF,CMOD and other crack parameters.

MODELING

A numerical model of a side edge notch bending specimen has been developed using ANSYS 15.0. Figure 3depicts the geometry and dimensions for the V-notched SENB specimen used for three point bending test. The three-point bending test is a destructive fracture test technique used for testing of ductile, brittle and quasi-brittle materials.

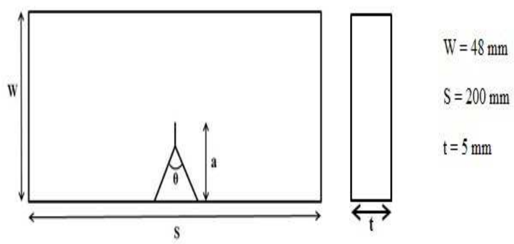
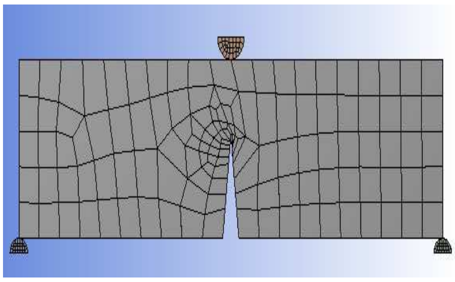
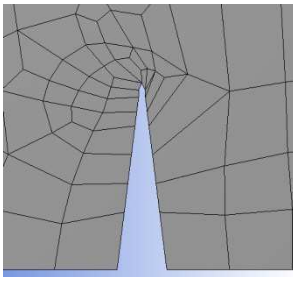


Figure 3: Dimensions of the Specimen, where, 'a' is Crack Length, 'S' is Span Length, 'W' is Width of the speCimen,'t' is Thickness of the Specimen, 'θ' is Notch Angle.

A model of the above geometry was created using ANSYS 15.0 and extruded up to 5 mm using structural steel as the solid material. The mesh was a coarse mesh containing 429 elements and 2900 nodes as shown in figure 4(a). A higher mesh density at the crack edges was chosen in order to obtain an accurate result





(a) **(b)**

Figure 4(a): Meshing of the Specimen (b) Meshing Near the Crack

A crack front was created on the edge anda pre-meshed crack was developed at the selected edge. Later, the boundary conditions and the loading were specified and the solution was generated.

THE SOLUTION

The analysis of V-notch crack was done at different crack angle range varying from 0^0 to 90^0 with a difference of 15^0. The crack length was also varied from 26 mm to 30mm with an increment of 1mm, and the load also varying from 500N to 1500N.

The effect of the variation of load, crack length and crack angle on the stress field around the crack tip has been studied.

Table 2: The Values of SIF and CMOD for Different Crack Length and Different Crack Angles

Sl. No.	Crack Length,a (mm)	Crack angle,θ (deg.)	Load(N)	CMOD(mm)	SIF(MPa.m$^{1/2}$)
1.	26	0	500	0.0116	27.861
2.	26	15	500	0.0114	35.415
3.	26	30	500	0.0110	34.573
4.	26	45	500	0.0107	23.435
5.	26	60	500	0.0105	30.939
6.	26	75	500	0.0099	28.190
7.	26	90	500	0.0095	24.316
8.	27	0	500	0.0119	33.364
9.	27	15	500	0.0113	44.761
10.	27	30	500	0.0113	34.835
11.	27	45	500	0.0113	26.706
12.	27	60	500	0.0106	29.022
13.	27	75	500	0.0101	28.650
14.	27	90	500	0.0096	27.476
15.	28	0	500	0.0112	29.048
16.	28	15	500	0.0112	30.679
17.	28	30	500	0.0115	28.284
18.	28	45	500	0.0111	29.434
19.	28	60	500	0.0108	27.837
20.	28	75	500	0.0103	26.861
21.	28	90	500	0.0094	31.373
22.	29	0	500	0.0134	45.514
23.	29	15	500	0.0020	30.991
24.	29	30	500	0.0116	27.913

Table 2: Contd.,

25.	29	45	500	0.0114	28.872
26.	29	60	500	0.0109	28.599
27.	29	75	500	0.0104	26.218
28.	29	90	500	0.0099	26.952
29.	30	0	500	0.0125	36.337
30.	30	15	500	0.0123	24.463
31.	30	30	500	0.0118	28.713
32.	30	45	500	0.0115	22.952
33.	30	60	500	0.0111	24.208
34.	30	75	500	0.0105	24.907
35.	30	90	500	0.0100	24.679

Table 3: The Variation of CMOD and SIF for Varying Load

Load (N)	CMOD (mm)	SIF ($MPa.m^{1/2}$)
500	1.1949E-02	33.364
600	1.4341E-02	40.037
700	1.6726E-02	46.709
800	1.9115E-02	53.382
900	2.1510E-02	60.055
1000	2.3879E-02	66.728
1100	2.6290E-02	73.4
1200	2.8670E-02	80.073
1300	3.1062E-02	86.746
1400	3.3460E-02	93.419
1500	3.5846E-02	100.09

THE RESULTS

The model so created, meshed and loaded was analysed under various conditions and data were generated. The data so generated have been tabulated and available through tables 2, 3 & 4. Table 2 contains the CMOD values and the SIF values for crack length varying from 26mm to 30 mm at an increment of 1mm at different crack angle ranging from 0^0 to 90^0 at an interval of 15^0 i.e. at 0^0,15^0,30^0,45^0,60^0,75^0 and 90^0 at an applied load of 500N.

Table 3 contains the value of CMOD and SIF at different loads varying from 500N to 1500N at a regular increment of 100N for the specimen model having a crack length of 27 mm and crack angle of 0^0.

Table 4 contains the value of stress at the crack tip for the specimen having crack angle 0^0 and crack length of 26mm at different loads ranging from 500N to 1200N.

Table 4: Values of Stress at Crack Tip for Different Load

Load (N)	Stress at Crack Tip (MPa)		
	$\theta = 0^0$	$\theta = 15^0$	$\theta = 30^0$
500	18.402	25.33	28.028
600	22.144	30.41	33.836
700	25.361	35.39	38.978
800	28.947	40.53	44.547
900	32.479	45.61	50.754
1000	36.43	50.62	56.393

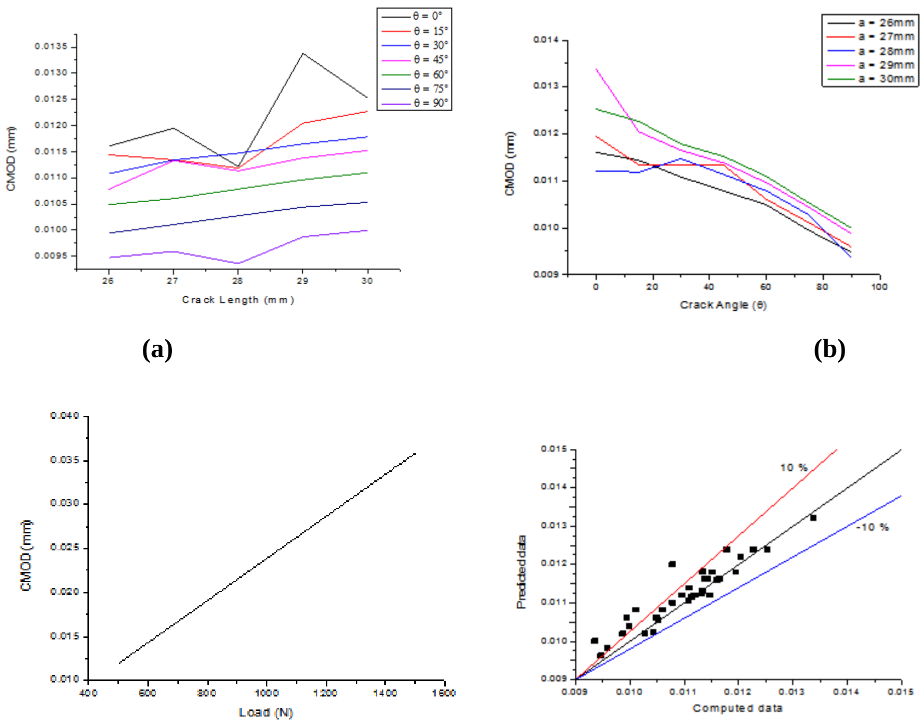
Table 4: Contd.,

1100	39.853	55.73	61.284
1200	43.421	60.79	67.672

PARAMETRIC STUDY

The effect of the crack parameters like the crack length, crack angle and the load applied has been studied on the underlying principles of solid mechanics. The variations are shown through figure 4-6.6.1. Effect on CMOD

The variation of CMOD with the crack parameters have been shown in the form of plots through figure 5. Figure 5(a) shows the variation of CMOD with crack length at different crack angle. It reveals that with the increase in the crack length for the same crack angle, the CMOD value increases, but the increase is very small. For a 15% rise in the value of crack length, there is around 6% rise in the CMOD value. The possible increase in the value of CMOD reveals that CMOD is a function of crack length which in turn increases with increase in load. It can also be observed from the plot that for a constant value of crack length, the CMOD value decreases with increase in the crack angle.



(a) (b)

(b) (d)

Figure 5(a): Plot Between CMOD and Crack Length at Constant Crack Angle. (b) Plot between CMOD and Crack Angle at Constant crack Length. (c) Plot between CMOD and load for a = 27mm (d) Comparison between Predicted and Computed Data

Equation 1 shows the correlation developed between the CMOD, crack length and the crack angle from the simulated data obtained.

$$\text{CMOD} = -0.002 * [\text{sine (crack angle)}]^{3.5373} + 0.0027 * (\text{crack length})^{0.4480} \quad (1)$$

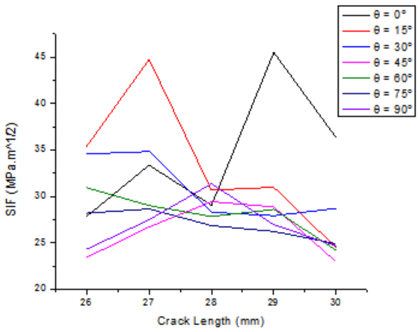
Figure 5(d) shows the comparison of the computed data (ANSYS) and the data obtained from correlation i.e. the predicted data. As can be clearly seen from the figure 5(d), the values lie between the error range of ±10%. This shows that

the correlation developed is in agreement with the results obtained from ANSYS, and hence fits best for calculating CMOD, with known crack angle and crack length.

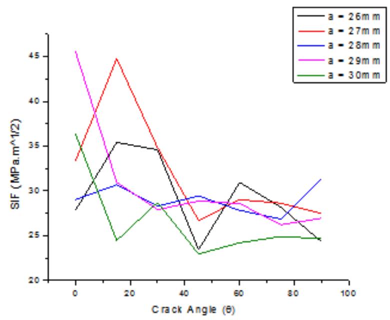
Figure 4(b) is a plot between the CMOD and the crack angle, where crack length is a parameter. This plot also shows similar variation as seen in figure. 4(a).i.e. when the crack angle increases the CMOD value decreases for a constant value of the crack length. Figure 4(c) shows the variation of crack mouth opening displacement with the load for the specimen model having a=27mm and $\theta=0^0$. The graph shows a linear variation of CMOD with the load applied.

Effect on Stress Intensity Factor

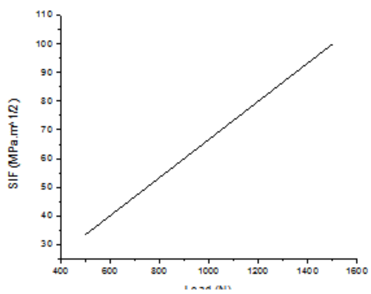
The variation in Stress Intensity Factor at different crack parameters have been successfully recorded using the numerical simulation. Figure 4 shows the plot of SIF with the different varying quantities. The SIF has been being kept on the Y axis, and the crack parameter on the X axis. Figure5(a) shows the variation of stress intensity factor with crack length. It has been noticed that for small crack angles i.e. for 0^0 and $15^0$the variation was random, but as the crack angle increases, the stress intensity factor first increased, reached to a maximum and then again started decreasing. The increase was recorded till the value of a/W reached approximately upto 0.6, after which again the stress intensity factor decreased. Figure 5(b) is a plot showing the variation of SIF with the crack angle for different crack length. It is clearly indicative that for a constant value of crack length as the crack angle increases the stress intensity values decreases. This behavior can be explained by the fact that with the growth of crack length, notch angle effects decreases on the crack parameters. Figure 5(c) shows the variation of the SIF with the load applied for the model with a = 27mm and $\theta = 0^0$. The linear graph between the two variables shows that as the load is being increased, the stress intensity factor at the crack tip also increases, which validates the fact that as the load is being increased the chances of the crack propagation also increases.



(a)



(b)



(c)

Figure 5: (a) Variation of SIF with Crack Length at Different Crack Angle. (b) Variation of SIF with Crack Angle at Different Crack Length (c) Variation of SIF with Load Applied for a= 27 and $\theta=0^0$.

Effect on Stress at Crack Tip

The variation of the stress at the crack tip due to the load applied has been shown in figure 6.

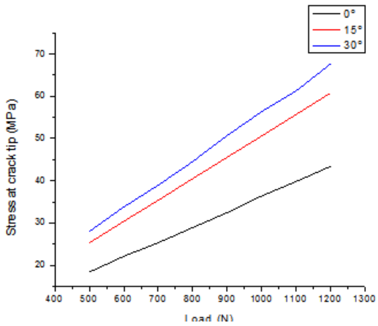


Figure 6: Variation of Stress at Crack Tip with Load

The plot shows that as the load is increased, the stress at the crack tip also increases. It can also be identified from the graph that with the increasing load, if the crack angle is increased, the stress level at the crack tip also increases. But, the slope of the line for an increased crack angle is more. This shows that as we go on increasing the crack angle, a small variation in load will cause a large variation in the stress at the crack tip.

CONCLUSIONS

The numerical study reveals that the CMOD and the SIF values for a V- notched crack is affected by the crack geometry and the loading conditions significantly. The following salient conclusions have been drawn from the study:

- The numerical value of CMOD increases with increase in crack length. However, the change is very small.
- CMOD decreases with increase in crack angle.
- CMOD increases with increase in load.
- With an increase in the crack angle, the SIF value till a $\leq$ 0.6 W, and then starts decreasing for further values.
- SIF decreases with increase in crack angle.
- The stress at the crack tip increases linearly with the increase in the load, but the slope goes on increasing as the crack angle is increased.

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